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DEVELOPMENT OF PARAMETRIC COST MODELS FOR WEAPON SYSTEMS.(U)
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(10) J. P. Large

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DEVELOPMENT OF PARAMETRIC COST MODELS
FOR WEAPON SYSTEMS

J. P. Large

April 1981

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(1)

Parametric cost models are not a recent development. If Cheops thought about cost at all when building the Great Pyramid he would have used expressions of the type Y = aX where X equals some parameter such as blocks of granite or number of slaves. Most estimating over the centuries and even today is in terms of cost per pound, cost per foot, cost per barrel or some other simple unit of measurement, all of which are simple parametric cost models. They were not recognized as such, and it seems to me it was not until the early 1960's that the term parametric cost model became part of the vocabulary of the defense community. Since then Rand and a number of other organizations have been diligently cultivating this field, and parametric cost models have grown in complexity and rigor to the point where they qualify for a session at an international meeting such as this one.

The limited time makes it necessary to limit the scope of this presentation, so my remarks will be limited pretty much to aircraft cost models, by extension they apply to weapon systems in general. Even the subject of aircraft cost models is a broad one. This display lists some of the models in use today.

AIRCRAFT COST MODELS

By type of structure: built-up skin stringer, integral skin stringer, machined plate ...

By basic structure: wing, horizontal stabilizer, vertical stabilizer, fuselage

By subsystem: airframe, engine, avionics

By functional cost element: engineering, tooling, manufacturing

By phase: development, production, operations

By organization: squadron, wing, command

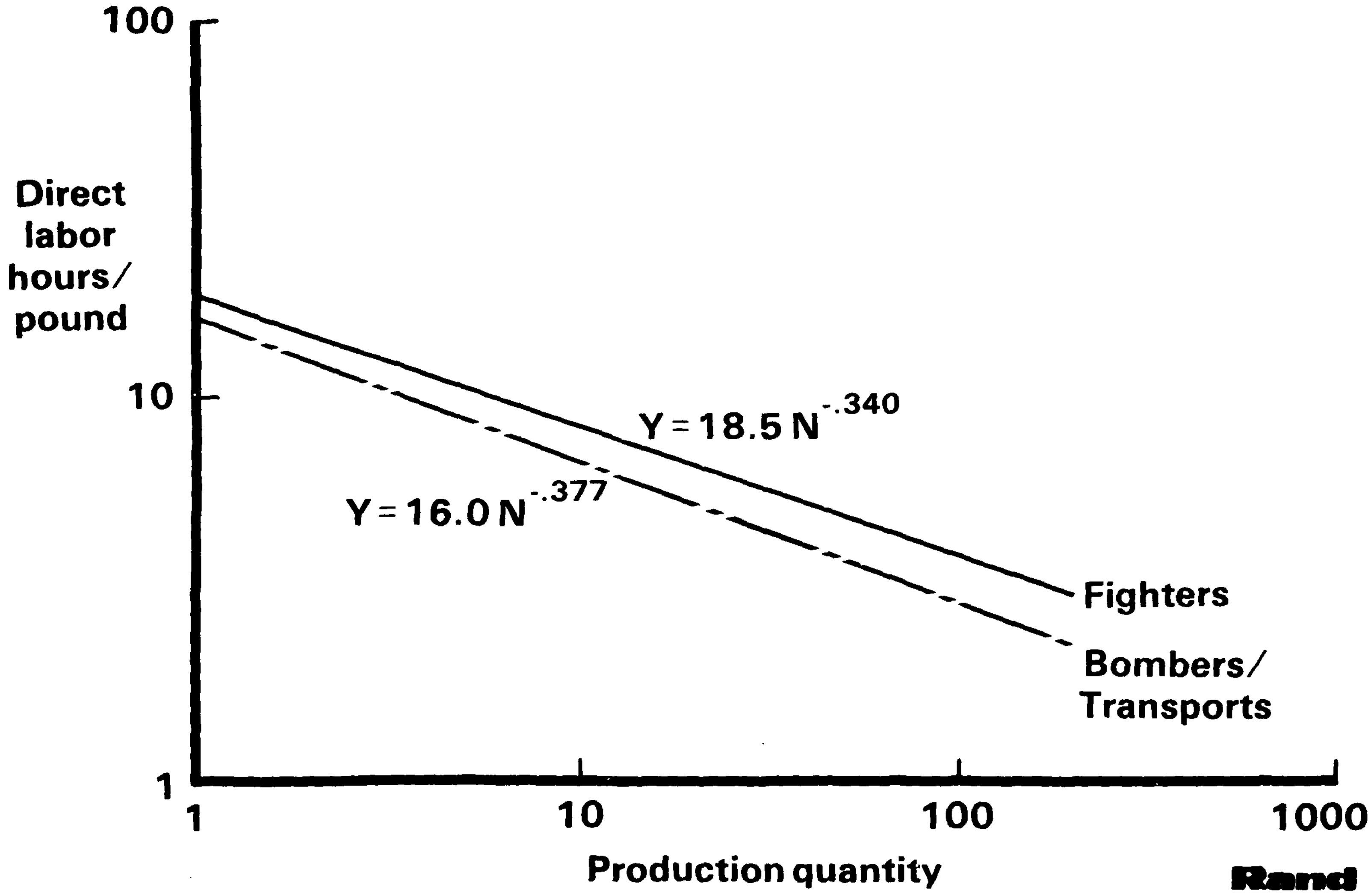
Rand

(2)

Each has its uses, and sometimes those uses are different from what was originally intended. In Rand reports on cost models, for example, you will always find a phrase warning the reader that the model is intended for use in long-range planning studies. The warning is sincere, but we know that the models are used for a variety of other purposes. They are used because the inputs can be obtained easily, the time and expense are minimal, and for DoD agencies generally there is no alternative. A grassroots estimate of the kind performed by industry is outside the capability of the military services.

The Air Force recognized the need for parametric cost models shortly after it was organized. In 1947 the Air Force published Source Book of World War II Basic Data: Airframe Industry [1], which presented a number of learning curves relating direct hours per pound of airframe weight to the cumulative number of aircraft produced.

1947 CURVES

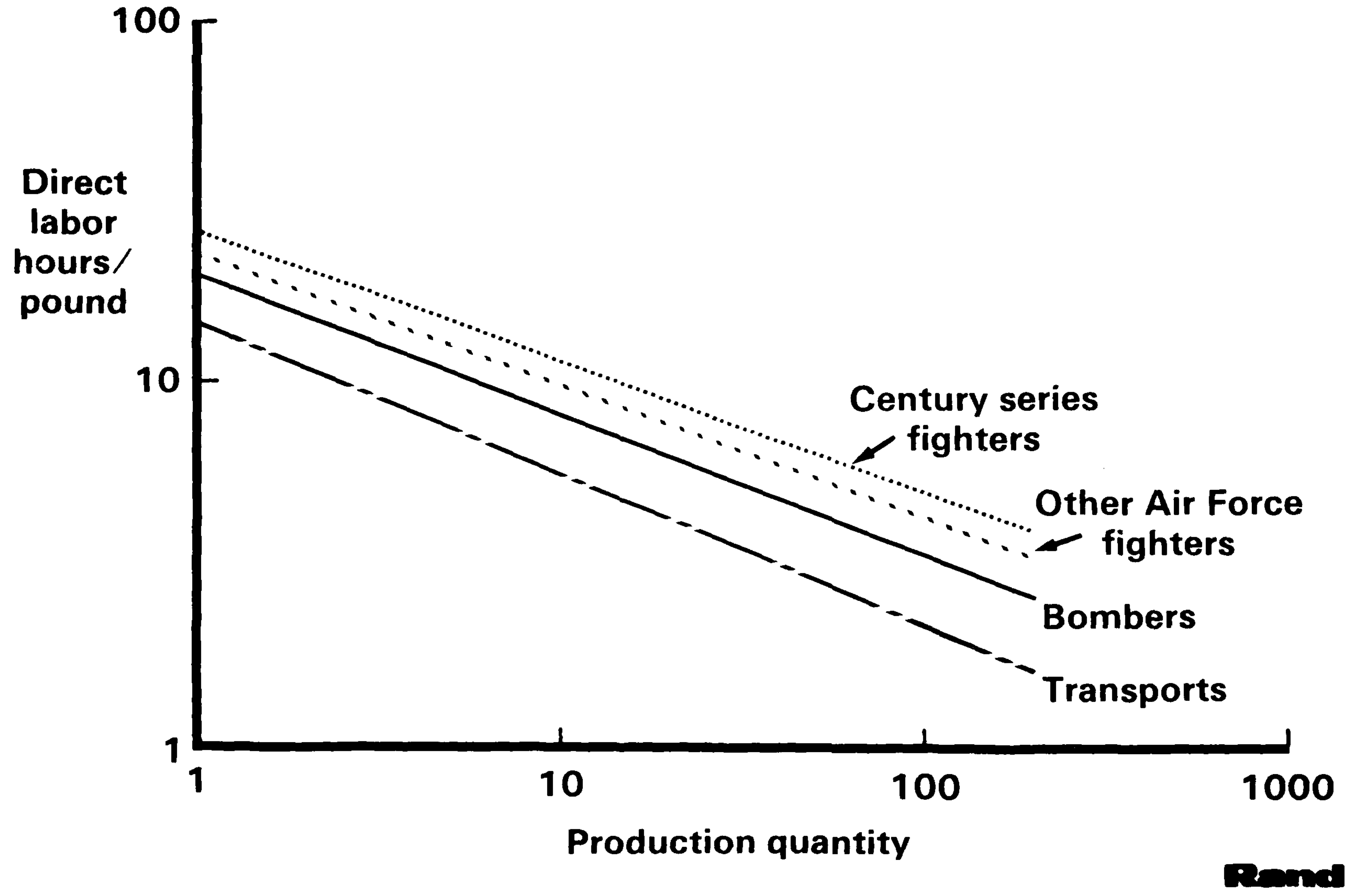

100
10
1
Direct labor hours/ pound
$Y = 18.5\,N^{-.340}$
$Y = 16.0\,N^{-.377}$
Fighters
Bombers/ Transports
1
10
100
1000
Production quantity
Rand

(3)

For quite a few years direct factory hours were estimated - not too badly - from models of that type. Most of the early statistical analyses focused on direct factory labor and learning curves. A 1956 Rand report, Cost-Quantity Relationships in the Airframe Industry [2], concentrated on how to estimate the slope of the learning curve, i.e., the b-value in the expression $Y = ax^b$, rather than the a-value, which is the direct hours per pound. The Air Force, however, continued to publish industry-wide data showing that direct labor hours were increasing. By 1960 the industry average for Century-series fighters was $25.86\ N^{-0.361}$, an increase of 40 percent over the 1947 figure. That raised the question of why Century-series fighters should require more direct labor than other fighters, and for that matter why bombers required more than transports.

With curves of the type shown no distinction was made between a 10,000-lb fighter and a 15,000-lb fighter; both had the same hours/pound. But the labor content of an item does not usually increase proportionately with weight. The relative positions of the fighter, bomber, and transport curves are due more to their differing sizes than to inherent differences in design.

1960 INDUSTRY-WIDE CURVES



(4)

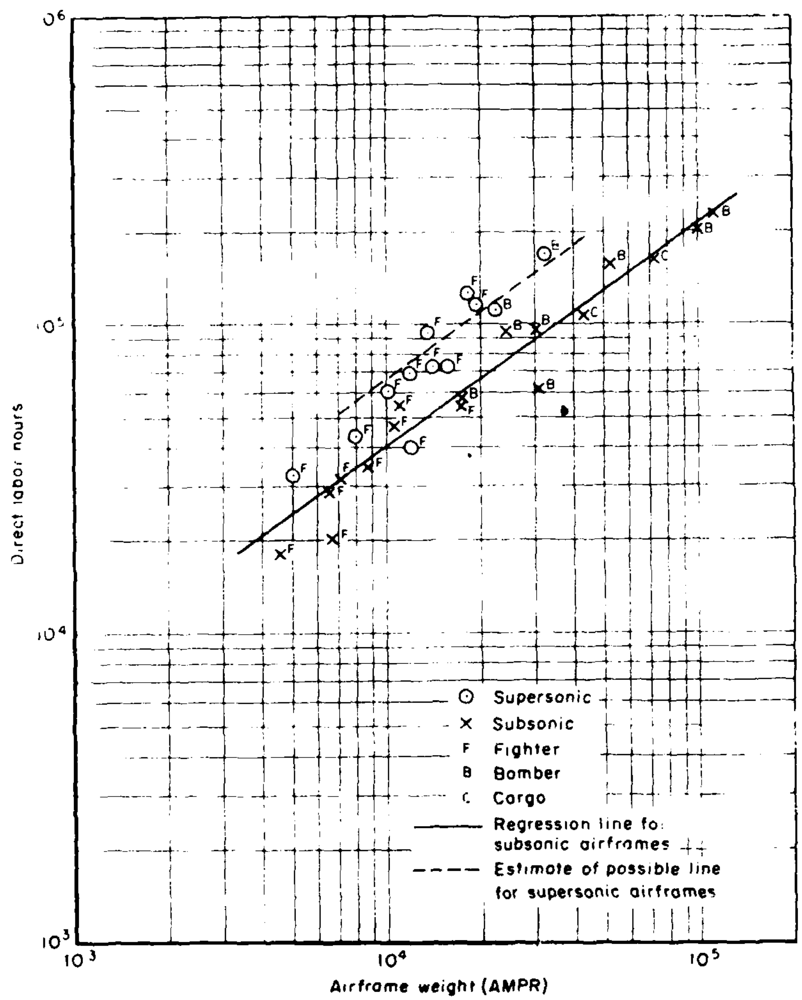
In looking at a plot of airframe data it was clear that fighters, bombers, and transports were *not separate* samples. A plot from a 1962 Rand report [3], shows that all three types are close to a regression line for subsonic aircraft. Supersonic aircraft with one exception are all above the line, thus suggesting that the critical distinction is speed, not type. When speed was added as another independent variable, it proved to be statistically significant, and the era of statistically derived parametric cost models had arrived at Rand.

The year was 1962, and statistics had not been a prominent feature of earlier cost analyses for several reasons. First, and this problem has not changed much, the data available were frequently too sparse to support statistical analysis. Statisticians were attracted to the reams of data published by the Air Force on World War II and post World War II aircraft, but more pressing questions of the 1950's and early 1960's concerned ballistic missiles and space systems. Parametric cost models were based on curves drawn through three, two, or sometimes one point.

A second reason that statistical analysis was not common will be appreciated only by those who can remember back to the pre-computer age. Several laborious hours on a Friden calculator were required to do what can be done today in five minutes on a pocket-sized hand calculator. The sheer volume of calculations required had a strong inhibiting effect on researchers.

DIRECT LABOR HOURS AT THE 100TH UNIT

(UNIT COST)



Rand

(5)

Also, back in those days people had to refer to tables of logarithms when presented with a parametric cost model such as this one.

Direct labor hours:

$$\log X_1 = -0.93496 + 0.64350 \log X_2 + 0.77811 \log X_3$$

Total engineering cost:

$$\log X_4 = -4.35530 + 1.74831 \log X_2 + 0.83263 \log X_3$$

Total tooling cost:

$$\log X_5 = -2.78057 + 1.09854 \log X_2 + 0.99700 \log X_3$$

Where: X_2 = Aircraft maximum speed (knots)

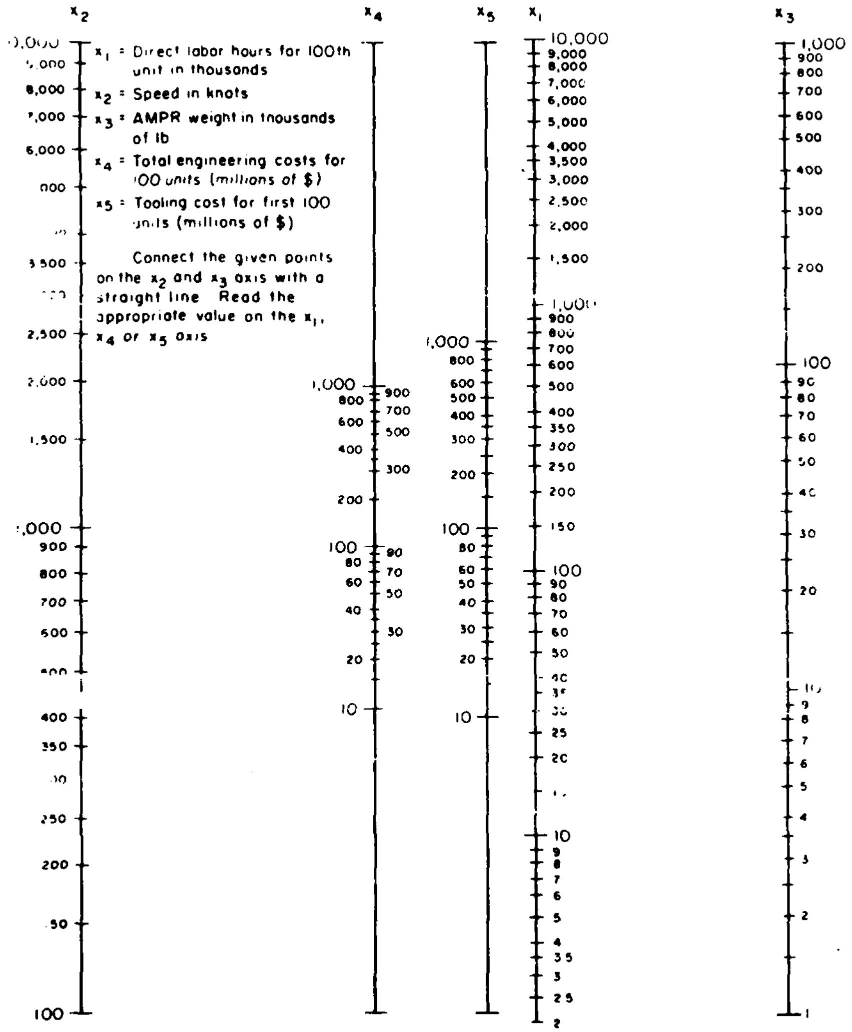
X_3 = Airframe weight (thousands of pounds)

Rand

(6)

For those who tend to confuse their mantissas with their characteristics the author produced a nomograph. The answers can be read directly, albeit imprecisely, by placing a straight-edge from X_2 to X_3. For example, the TFX, later to become the F-111, was a topic much discussed in 1962 because of controversy over cost and the awarding of the contract to General Dynamics instead of Boeing. Use of this nomograph would have given an estimate of approximately 200,000 direct labor hours or 6 hr/lb for the 100th unit.

NOMOGRAPH FOR ESTIMATING LABOR, ENGINEERING AND TOOLING



Rand

(7)

That estimate is shown here along with the contractors' estimates and the actual. Although the parametric estimate is low it gave notice at the time that the bid estimates were questionable.

Model	Date	Estimate of factory hr/lb at Unit 100
Fighters	1947	3.9
Century-series fighters	1960	4.9
Rand nomograph	1962	6.0
Boeing	1962	2.0
General Dynamics	1962	3.8
Observed	1968	7.0

Rand

(8)

A few years later the computational problem was solved as computers and statistical programs became available and were relatively cheap to use. The data problem remained as intractable as ever because manufacturers of military equipment prefer not to disclose their costs to anyone, and costs reported to the government are seldom the kind needed by analysts. One effect of that was to continue working on aircraft airframes where Rand had compiled a substantial data base over the years.

The result was a 1966 report [4] that presented a complete parametric cost model for the development and production of airframes. It followed the general pattern of the earlier study, but despite a search for additional independent variables that would explain more of the variance, the conclusion was that weight and speed (or thrust as a proxy for speed) were still the only two that could be justified statistically.

Not everyone shared that conclusion. OSD/Systems Analysis gave Planning Research Corporation a contract to develop an airframe model at about that time, and that model had a variety of interesting variables [5]. Some were judgmental rather than statistically significant, but statistical purity is not an essential feature of parametric cost models. Too much insistence on it results in the elimination of useful variables. Figure 8 lists the PRC variables and the cost elements they are associated with. Note that speed at sea level was found to be a better explainer of direct labor hours than speed at altitude, but the opposite was true for the other three cost elements. The ratio $\frac{\text{Empty weight-airframe unit weight}}{\text{Airframe unit weight}}$ was an attempt to introduce something like a complexity factor into the model. The model asserts that development costs of Naval aircraft are substantially higher than those of Air Force aircraft; and if the user is unable to estimate weight growth, the model will make that estimate for him. All in all it was a useful model for its time, but it did not establish a pattern for future work.

Explanatory variable	Nonrecurring engr. & tool	Recurring engr. & tool	Factory dir. labor	MFG materials
Maximum speed at sea level			√	
Maximum speed at altitude	√	√		√
$\frac{\text{Empty wt - Airframe unit wt}}{\text{Airframe unit wt}}$	√	√		
Prototype vs. full-scale development	√			
Air Force vs. Navy	√			
Airframe weight growth		√	√	
Year of first delivery		√		√
Delivery rate			√	√
Airframe unit weight			√	√

Rand

(9)

Rand continued to update its airframe models but without any change in format. The reason was that contractors traditionally report costs by functional cost element and that is the way the Air Force prefers to estimate them. The accuracy of the overall estimate is always better, however, than the accuracy of the individual elements, because the data are inconsistent at the cost-element level. What one company calls engineering another company calls tooling, or a given company will change definitions to conform to cost-accounting standards, and it has never been possible to adjust the data to eliminate all discrepancies. At the highest level - aircraft cost - comparisons are most valid.

The U.S. Navy contracted to have an airframe model developed in 1972 that had only two cost elements - nonrecurring and recurring costs [6]. A second major change is that a novel index of technological advance was introduced, and a third was that a judgment about complexity was required of the user. The index of technological advance was truly innovative. A review of technological advances had led to the conclusion that they were occasioned in most cases by the demand for increased fighter performance. From that conclusion it was reasoned that the introduction of every new fighter was a step forward in technology. An index was put together beginning with the Nieuport 11 in 1915 and extending up through the F-14. To estimate airframe cost an index number could be inferred from that list.

J. W. NOAH MODEL

$$C_1 = -5.945 + .00663S + .05138T - 1.4071R + 6.7492\delta$$

$$C_2 = -105.05 + .11557S + 1.2034T - 1.0248A + 97.631\delta$$

Where: C_1 = NR \$/lb of airframe weight (000)

C_2 = R \$/lb of airframe weight (CAC 100)

S = Maximum speed at altitude (kn)

T = Technical index

R = Gross takeoff weight/airframe weight

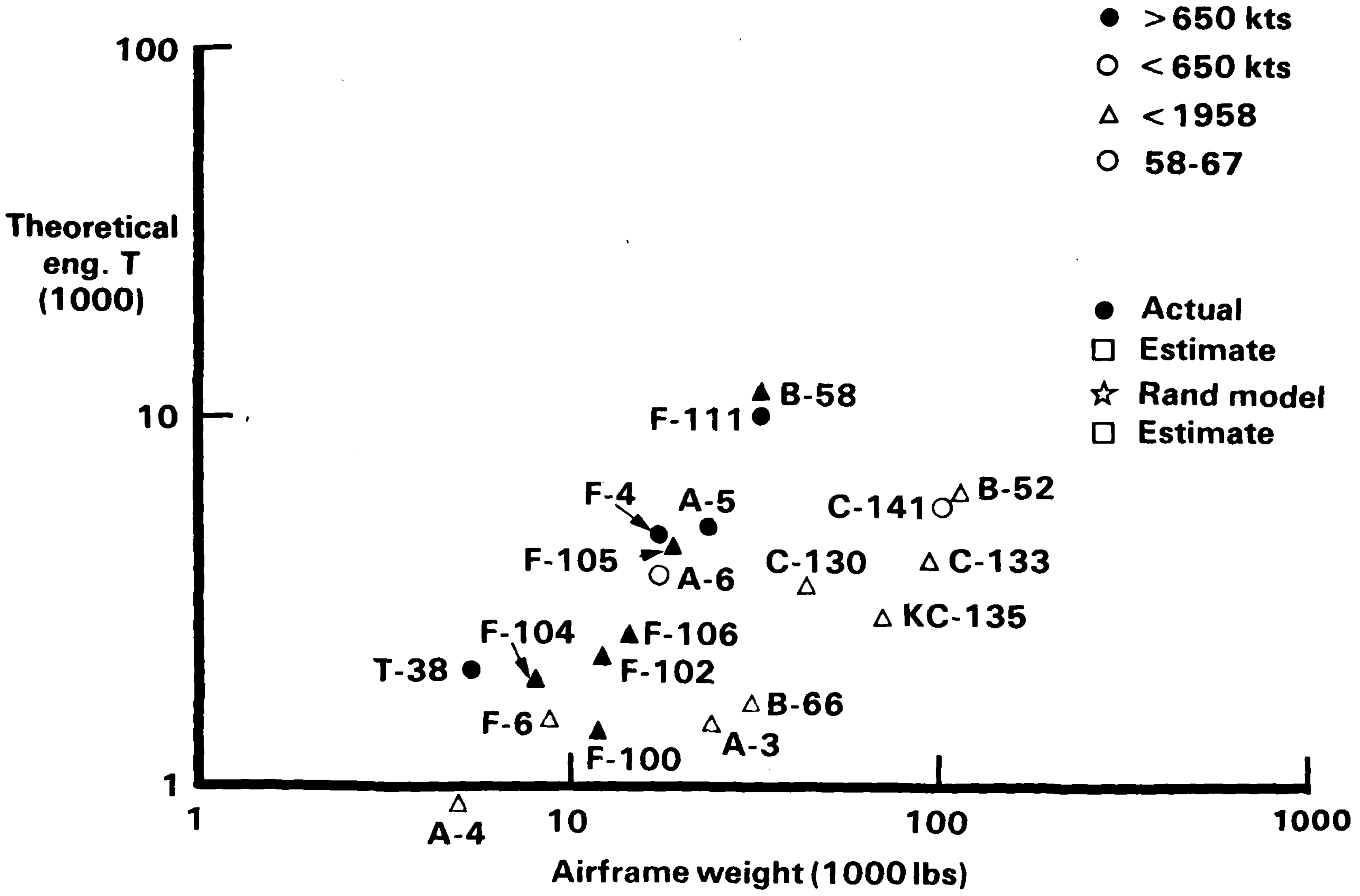
δ = Complexity dummy (0 or 1)

A = Airframe weight

Rand

(10)

That index and the judgmental complexity factor get at the root of the estimating problem. Physical and performance factors such as weight and speed are not sufficient in themselves to deal with next generation aircraft, but some judgmental factors are too unreliable to include in a parametric cost model. I tried an experiment at Rand several years ago in which several engineers considered knowledgeable about aircraft were asked to examine plots showing actual data on a sample of aircraft plus an estimate based on a cost model having only weight and speed as inputs. Here is one of the plots for the C-5A. On the basis of that information and all of their hindsight the engineers were asked whether the estimate should be adjusted and if so, how? Perhaps the experiment was poorly devised, but the results seemed to say that judgment is as likely to degrade the estimate as to improve it.



100
10
1
Theoretical eng. T (1000)
1
10
100
1000
Airframe weight (1000 lbs)
> 650 kts
< 650 kts
< 1958
58-67
Actual
Estimate
Rand model
Estimate
B-58
F-111
F-4
A-5
C-141
B-52
F-105
A-6
C-130
C-133
KC-135
F-104
F-106
T-38
F-102
B-66
F-6
A-3
F-100
A-4

Rand

(11)

What the estimating world is continually looking for is something like the Time-of-Arrival equation developed at Rand a few years ago for military jet engines [7]. That equation combines a number of engine characteristics - turbine inlet temperature, total pressure, weight, specific fuel consumption, and maximum thrust - to get what is in effect a technological index.

AIRCRAFT TURBINE ENGINE TIME-OF-ARRIVAL (TOA) EQUATION

$$TOA26 = -856.4 + 110.10 \ln TEMP + 11.41 \ln TOTPRS - 26.08 \ln WGT - 16.02 \ln SFCMIL + 18.37 \ln THRMAX$$

$R^2 = 0.96$
SE = 6.9
F = 92 (5, 20)

EXAMPLE: J79 ENGINE

VARIABLE	VALUE	CALCULATION
Constant	-856.4	-856.4
TEMP	2160	+845.3
TOTPRS	18056	+111.8
WGT	3225	-210.7
SFC	.87	+2.2
THRMAX	15000	+176.6
TOA26		68.8
MQTQTR		57

(12)

That index, TOA, was then used in an engine cost model with not completely satisfactory results [8]. One problem with variables based on time is that they must be updated every year or two or the estimates begin to deteriorate.

A similar index was developed at Rand for fighter aircraft [9] that attempted to predict first flight date based on a combination of performance variables. The best equation included specific power, sustained load factor, frequent range, payload fraction, and carrier capability. Unfortunately, technological advance as measured by those variables appeared to be totally unrelated to aircraft cost.

COST MODEL FOR THOUSANDTH PRODUCTION UNIT SELLING PRICE

(IN MILLIONS OF 1975 DOLLARS)

$$\ln \text{KPUSP} = -8.2070 + 0.70532 \ln \text{THRMAX} + 0.00674\ \text{TOA26} + 0.45710 \ln \text{MACH} + 0.01804\ \Delta\text{TOA26}$$

$R^2 = 0.951$
SE = 0.215
F = 63.0 (4, 13)

<u>EXAMPLE:</u> J79 ENGINE

VARIABLE	VALUE	CALCULATION
Constant	-8.2070	-8.2070
THRMAX	15000	6.78222
TOA26	68.8	0.46371
MACH	2.0	0.31684
Δ TOA26	11.8	0.21287
ln KPUSP		-0.43136
KPUSP		0.650
Actual KPUSP		0.631

(13)

The Rand engine model was based entirely on statistical analysis. An alternative approach being pursued at about the same time by the Naval Air Development Center was to begin with a hypothesis about the factors that should influence R&D cost and to establish a parametric relationship without regard to the coefficients. The hypothesis is shown here. The first independent variable says that turbine inlet temperature governs engine performance and dictates engine complexity. The second says that the development effort required to achieve a specific TIT reduces with time. The third stipulates that afterburning engines cost more to develop because of the additional design and testing required.

Regression analysis was then used to determine whether the three hypotheses could be justified, and a useful parametric cost model was obtained [10].

DEVELOPMENT COST METHODOLOGY

ENGINE DATA BASE

J52	TF30
J57	TF33
J58	TF34
J60	TF39
J75	JT8D
J79	JT9D
J85	
J93+	

+ NON QUALIFIED

STEPWISE LINEAR REGRESSION

$$\$ = A_1 + A_2 TIT - A_3 MQT + A_4 \delta_{AB}$$

$\sigma = 23.3\overline{M}$ (CY69)

CORR. COEF. = .979

(14)

"Useful" in this context means useful for trade-off studies of next-generation aircraft where relative costs are more important than absolute costs. Such models are useful for detecting gross discrepancies in estimates by advocates of a particular model or system. And they are useful where the only information available is a few key parameters such as weight, speed, thrust or range. By and large they are developed by statistical analysis of experienced costs.

The goal for such models is to achieve an accuracy of plus or minus 20 percent. This chart shows for a sample of six airframe models how often that goal is achieved [11]. Deviations on the A-7 also show inadvertently how getting consistent data is a continuing problem. We had queried the manufacturer specifically about the engineering hours in our data base for the A-7 because they seemed abnormally low. After the report from which this table is taken was published we discovered that because of confusion over definitions about 1.5 million engineering hours had been excluded. Their inclusion would reduce the A-7 deviations substantially.

The time trend is encouraging. When the A-7 is disregarded, the deviations exceeding 20 percent drop from four in the first Rand model to zero in the second Noah model. The good score achieved by the latter is based on being able to distinguish between a major technology advance and a moderate technology advance before an aircraft begins development. My experience is that such judgments are often fallacious, but the point of the chart is that we are making progress.

DEVIATIONS FOR NINE POST-1960 AIRCRAFT[a]

(PERCENT)

Aircraft	Rand 1966	PRC 1967	Rand 1971	JWN 1973	Rand 1976	JWN 1977
A-7	-79	-108	-79	-29	-85	-25
A-10	19	8	17	19	6	9
C-5	-11	-34	12	--	9	- 4
C-141	-74	-76	-44	-3	-44	-15
F-4	-31	12	-11	32	-5	10
F-14	-53	-9	-33	10	-18	4
F-15	-14	25	-2	5	4	-12
F-111	-14	20	4	0	14	11
S-3	57	28	48	1	40	6

[a]Based on total development and production cost of 100 aircraft.

Rand

For this type of model that requires only a few inputs early in a weapon system's life-cycle I am not sure that much improvement is possible. Their great advantage is that they implicitly assume that a development program will have its full share of problems and that production will not be at a highly efficient rate. More detailed models take into account design differences, schedule, volume of business, and a number of other program-peculiar characteristics. They offer a promise of greater accuracy, but also of greater inaccuracy if early assumptions are over-optimistic.

The trend towards greater detail and complexity is the path of evolution. One-celled models evolve into two-celled models and eventually, if you agree with the theory of natural selection, you could have a model the size of the woolly mastodon, which would probably receive the same fate. Let me note that parametric cost models are developing in another way as well. They are being used for many purposes far removed from weapon systems - for estimating the costs of new industrial cities in Saudi Arabia to give one example. Thus, old problems may have been solved, but new ones are taking their place. I am sure that you people with your fresh ideas and new techniques will progress more quickly toward solutions than we have in the past.

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